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Experimental Observations of Naval Space Surveillance Satellite Signals with an Out-of-Plane Receiving Station

S. H. KNOWLES AND W. B. WALTMAN

E. O. Hulburt Center for Space Research

R. H. SMITH

Naval Space Surveillance System
Dahlgren, VA

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Experimental observations were made during May 1981 of satellites transiting the Naval Space Surveillance System's radio frequency fence. The receiving station's location at Riverside, Maryland is well out of the plane of the NAVSPASUR fence; this made possible testing the efficiency of an out-of-plane station in enabling single-pass orbit determination. A signal-processing algorithm was developed that made possible the extraction of an additional item of information from each satellite transit by chirp processing. It was concluded that both an out-of-plane station and chirp processing have promise for enabling single-pass NAVSPASUR orbit determination.

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Executive Summary

This report describes the results of work performed for the Naval Space Surveillance System by the Radio and Infrared Astronomy Branch of the Naval Research Laboratory. As part of an effort to upgrade the single pass orbit determination capabilities of the NAVSPASUR satellite tracking network, satellite echos from the NAVSPASUR transmitters were received and recorded at the Maryland Point Radio Observatory, Riverside, Md. The goals of the experiment were to determine the distribution of signal strengths of the echos, the accuracy obtainable in doppler frequency determinations, and through detailed signal analysis to measure the characteristics of the individual echos. When combined with a computer analysis of orbital parameter sensitivities this data provides information on the accuracy improvement obtainable from the addition of new receiving stations out of the plane of the present system and gives the signal parameters needed for the design of these stations.

A total of 165 satellite passes were recorded and Fourier transform processed for detection and measurement of signal strengths, arrival times, and doppler shifts. Over 75% of the passes were detected, many from more than one transmitter station. The range of signal strengths was comparable to that from the in-plane stations. A fine grain Fourier analysis performed on a selected sample of returns showed that the returns had a chirp signature which could be measured to an accuracy of ±1-5 Hz/sec, with a doppler measurement accuracy of ±1 Hz.

A comparison of these results with the orbital parameter sensitivities shows the potential for dramatic improvements in the single-pass measurement of plane-normal velocity by implementing the advanced signal processing techniques used in this experiment.

A

EXPERIMENTAL OBSERVATIONS OF NAVAL SPACE SURVEILLANCE SATELLITE SIGNALS WITH AN OUT-OF-PLANE RECEIVING STATION

Introduction

The Naval Space Surveillance System consists of a "fence" of 217 MHz radiation, located in a great circle across the southern part of our country, which is of necessity crossed periodically by all satellites overflying the United States. Three transmitting stations, located approximately along an east-west line, establish the fence. A series of receiving stations use interferometry to establish the direction cosines of a satellite when the fence is crossed(5). The satellite doppler shift at the time of fence crossing is also available. Because no co-operation is required from a satellite to measure its position, and because of its ability to pick up essentially all satellites, the NAVSPASUR system is a central element of our Defense Department satellite tracking and warning facilities.

The NAVSPASUR system as presently constituted can measure 5 of the 6 independent parameters needed to determine a satellite orbit accurately in one pass. The sixth parameter, the component of velocity normal to the NAVSPASUR fence plane, cannot be measured well because of the geometry involved. Since it is of considerable interest to be able to determine all parameters of a satellite pass well with only one observation, attention has been paid to the possibility of eliminating this deficiency(4).

One possible solution is to establish one or more receiving stations located a significant distance north or south of the present fence in order to eliminate the existing geometrical singularity. In order to provide experimental evidence to verify this, observations were undertaken by the NAVSPASUR management. The facility used for this experiment was the radio astronomy observatory at Riverside, Maryland belonging to the U. S. Naval Research Laboratory. This observatory contains two large fully steerable parabolic antennas with diameters of 85 feet and 84 feet; they are fully efficient at the NAVSPASUR frequency. In addition, NRL has available a wide variety of auxiliary electronics, as well as personnel with experience in receiver design and signal processing. The Maryland Point Observatory's geographical location at $\phi = 38° 22' N$, $\lambda = 77° 14' W$ is within 15 statute miles of the naval base at Dahlgren, Virginia, which is a prime candidate for the construction of an out-of-plane station.

This report describes the results of two 8-hour observing sessions conducted during May, 1981, during which 165 satellite passes were recorded. A complete data processing system was developed for the experiment, and optimal signal analysis methods were applied that made possible the extraction of an additional item of information from each satellite transit by chirp processing, as well as more accurate doppler shift determination. It was concluded that an out-of-plane station near Dahlgren, Va. has promise for enabling single-pass NAVSPASUR orbit determination. The results of the chirp processing indicate that single-pass orbit determination is also possible by applying this technique at the existing NAVSPASUR receiving stations.

Manuscript submitted March 31, 1982.

Receiving System

The 85-foot antenna of the Maryland Point Observatory was used for this experiment. It is a precision equatorially-mounted antenna used for radio astronomy observations at frequencies up to 53 Gigahertz. The surface and pointing accuracy greatly exceed that required at the NAVSPASUR frequency of 217 MHz. A Clavin type of dipole feed was designed and fabricated for use at 217 MHz. The feed is linearly polarized. A block diagram of the receiving system is shown in Figure 1. A noise diode and coupler provide the reference for measurement of the receiver noise temperature and the received power. The first local oscillator was adjusted to place the predicted doppler signal for each object observed at 2.2 kHz. A 1.0 kHz reference tone at a level of 10 dB below the system noise level was added into the signal channel. A time code was written on the other recorder channel. The measured parameters of the system are given in Table I.

To verify the performance of the receiver system and to measure the efficiency of the antenna with the 217 MHz feed, the radio source Taurus A (the Crab Nebula) was observed on May 5, 1981. A copy of the chart record is shown in Figure 2. These observations give the result

$$T_{Crab} = 0.83\ T_{cal}$$

or, for $T_{cal} = 70$ K,

$$T_{Crab} = 58\ \text{K},$$

where T stands for equivalent antenna temperature, defined by the equation below. For an antenna observing a radio source small compared to the antenna beam(1),

$$T_A = \frac{S\ \eta\ A_p}{2\ k}$$

where S is the flux density of the radio source in $W \cdot m^{-2} . Hz^{-1}$,
η is the efficiency of the antenna,
A_p is the physical area of the antenna in m^2,
and k is Boltzmann's constant = $1.38 \times 10^{-23}\ J \cdot K^{-1}$. For the 85' diameter antenna at Maryland Point, $A_p = 527\ m^2$. The flux of the Crab Nebula has been measured as 1880×10^{-26} Jy at 81.5 MHz, and 1430×10^{-26} Jy at 152 MHz(2). A logarithmic extrapolation gives $S = 1223 \times 10^{-26}$ Jy at 217 MHz. Therefore,

$$\eta = \frac{2\ k\ T_A}{S\ A_p} = 0.25$$

This efficiency, while somewhat low, is not unreasonable for low frequency dipole feeds. The gain of the 85' antenna is:

$$G = \frac{4\ \pi\ \eta\ A_p}{\lambda^2} = 869 = 29.4\ \text{dB}$$

at 217 MHz. Thus the 1 kHz reference tone corresponds to an isotropic received power (i.e. the power that would be received with a 0 dB gain antenna) of -172.4 dBm. Referenced to the receiver input, this number differs by the antenna gain the equivalent value is -143 dBm. The antenna beamwidth was measured to be 3°.25 by observing the sun drift through the antenna beam.

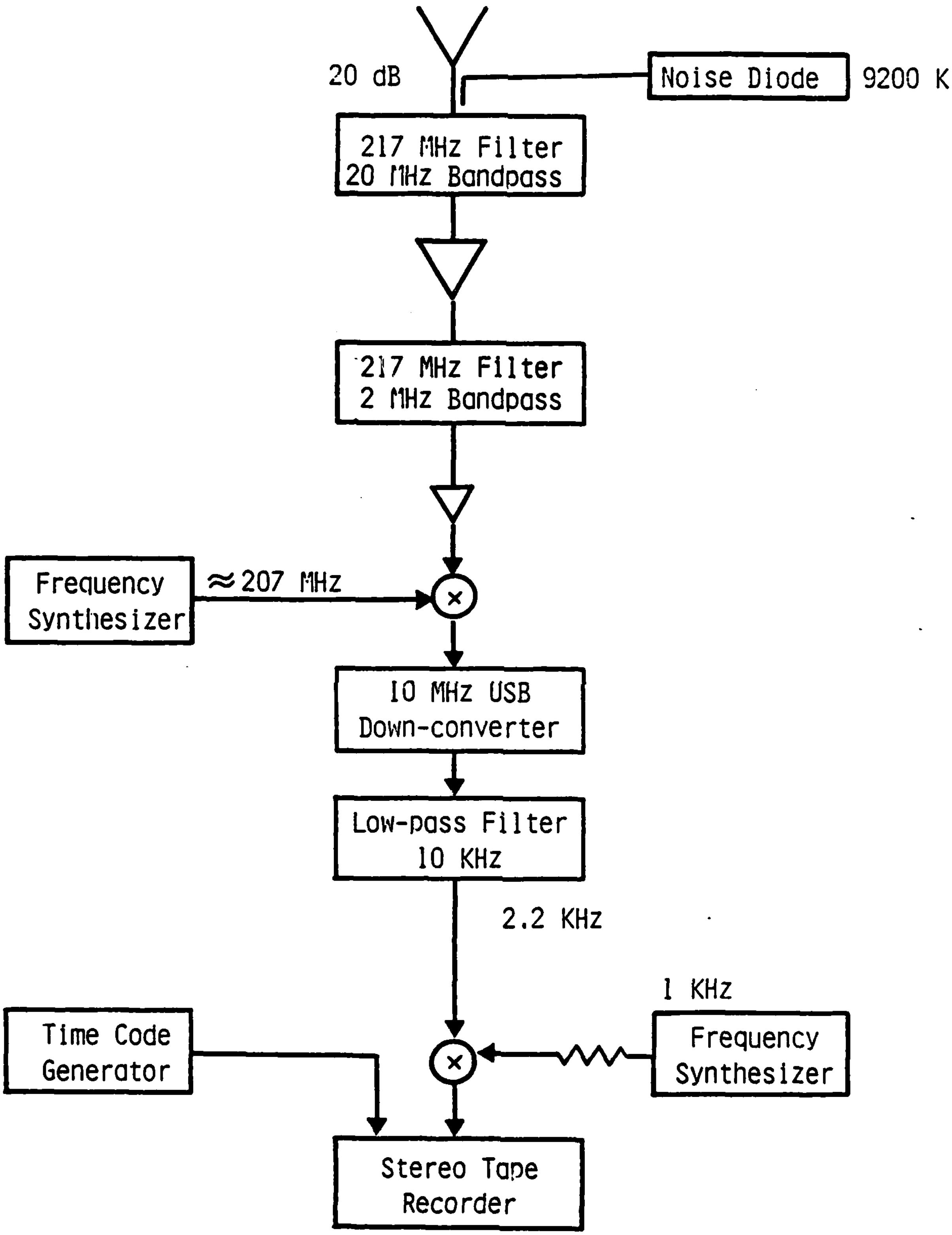

Fig. 1 — Block diagram of receiving system

Table I — Maryland Point receiving system parameters

Antenna Gain	29.4 dB
Feed VSWR	2.1
Feed Line Loss	0.5 dB
Coupler and Input Filter Loss	0.5 dB
Calibration Coupling Factor	21.7 dB
Noise Diode Excess Temperature	9200° K
Effective Calibration Temperature (at feed)	70° K
System Noise Temperature	385° K
Calibration Power in 10 kHz Bandwidth	-133 dBm
Reference Tone Power	-143 dBm

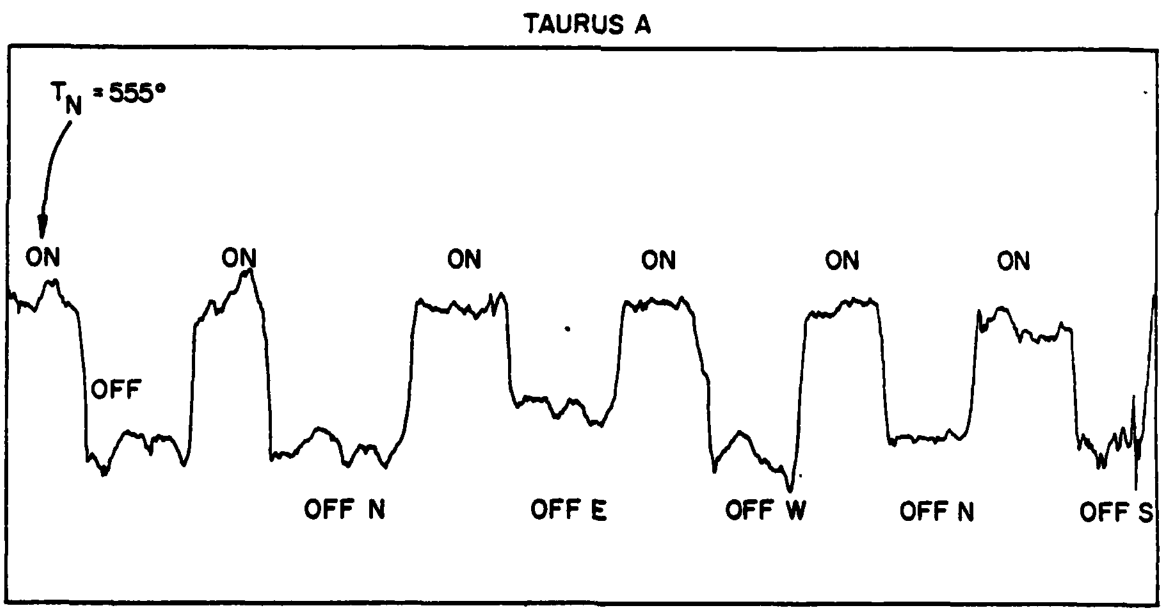

Fig. 2 — Taurus A chart record. The first "on" segment is the signal from the noise calibration; the others are received flux from the radio source Taurus A.

Satellite Observing

Observations were made during two eight-hour periods on 7 and 8 May 1981. As many satellite passes as possible were observed from a predicted list furnished by NAVSPASUR. The achieved rate was about 1 pass per 5 minutes, limited primarily by the finite slewing speed of our 85-foot antenna (about 15°/minute in each axis). A total of 192 objects were observed. The data from these satellite passes were then recorded on a standard reel-to-reel audio tape recorder, together with a locally generated time code on the unused channel. Amplitude modulation was used. The tape recorder was run continuously. This enabled us to analyze the full pass, including the time interval before the return was detected. The audio passband recorded was from about 20 Hz to 12000 Hz; a synthesizer (Fig. 1) was adjusted so that the predicted signal with the most negative doppler shift fell at the audio frequency of 2200 Hz. This meant that received signals almost always fell into the audio band 2000-4000 Hz. We also recorded a test tone at 1000 Hz with a constant amplitude about 10 dB below that detectable on a spectrum analyzer; this signal was later used to calibrate the amplitude of the received signals. We also monitored the passes by ear on a loudspeaker to get an approximate indication of signal strength,and detected 131 out of the 165 passes listed in Appendix A.

Data reduction

All our signal processing was done (not in real time) using a Hewlett-Packard 2116C mini-computer, programmed in the Forth language†(6). Our first step in data reduction was to digitize an interval from T_0-4 seconds to T_0+2 seconds surrounding each satellite pass.

The video signal was digitized under software control by the computer. Samples were taken at a 20 kHz rate controlled by a synthesizer; this resulted in a 10 kHz digital bandpass. Since the analog bandpass had a gradual falloff that extended somewhat above this, slight aliasing effects occurred in the upper part of the bandpass. This effect was not significant in the 2-4 kHz segment where signals normally occurred. The time window was opened and shut by an interrupt generated by the real-time clock. The data was digitized using the one-bit method extensively used by radio astronomers(3), whereby only the polarity of the signal is recorded. The use of this method very much eases timing and data storage problems associated with sampling the data. It can be shown that, for Gaussian signals, the one-bit method is completely equivalent to full amplitude sampling with only two exceptions. First, the signal-to-noise ratio is decreased by $\pi/2$ = 1.9 dB; second, the absolute signal power is lost, but can be recovered by means of a calibration signal. The characteristics of this method have not been rigorously derived for non-Gaussian signals; we assumed it to apply, and found no contraindication.

Actual signal processing consisted of two parts. The first preliminary solution analyzed the signals with a resolution of 20 Hz over a time window of 1.0 seconds by averaging twenty 1024-point Fourier transforms

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† The Forth programming language, which has many unusual features, is a very powerful tool for the analysis of real-time data on a mini-computer. However, its recursive nature makes a program listing difficult to comprehend. For this reason software documentation in this report is limited to flow diagrams.

of the one-bit data. A flow diagram of this signal processing is shown in the accuracy required, we had a few practical difficulties with our clock that decreased the accuracy of our time-of-arrival measurements. During the entire first day (May 7), the master clock was improperly synchronized. We estimate it to have been about 0.6 $\pm$ 0.1 seconds slow, so that a satellite that was "on-time" would appear 0.6 seconds early. This error was rectified on May 8, so that the clock was accurate to within 10^{-6} seconds; but the clock was discovered at the end of the day to have "dropped" 1.000000 seconds. Examination of the data showed that this error apparently occurred only very shortly before it was noticed.

The results of the routine analysis are shown in Appendix B. The satellites are identified by their NAVSPASUR satellite number; orbital information can be found in the NAVSPASUR satellite summary(7). The quantities shown are the measured amplitude and doppler frequency for each of the 3 NAVSPASUR transmitters. Amplitude is given in units of dBm, with the 1000 Hz reference assumed to be -172 dBm. Where a column for the transmitter was omitted entirely it means that the signal from that transmitter was not predicted to be visible from Maryland Point. "Not detected" means that the signal did not exceed about -182 dBm. "Unable" means, for Wetumpka and Gila River, that the predicted return frequency was within 40 Hz of the generally stronger Kickapoo return, making them impossible to distinguish using this method. Certain of these signals were later found using the fine grain analysis described below. Satellites ## 4-8 are actually calibration signals used to test the software and hardware; the injection frequency of each was 2200 Hz. Fig. 4 indicates the linearity of measurement of our system, as measured from these test signals. The minimum detectable signal is about -182 dBm from our signal analysis. (This number refers to actual received signal strength. Referred to the receiver terminals all signal strengths are higher by the antenna gain of 29.4 dB.) With this analysis we detected 125 of 166 passes (a few were eliminated from consideration because of various technical errors on our part). We detected 75 of 152 possible Wetumpka passes; the Wetumpka signal was on occasion almost as strong as the Kickapoo signal in spite of the much smaller transmitted power. We detected 16 of 90 possible Gila River passes; all of these detections were weak or marginal.

The production processing gave a generally faithful representation of basic signal characteristics. A principal defect was that the system measured average received power over a fixed 1.0 second window. This resulted in occasionally "missing" satellites that arrived appreciably earlier or later than predictions. Fig. 5 shows the cumulative distribution of received signal strengths from our experiment. The received signal strengths covered a wide range. The strongest received Kickapoo signal was -151 dBm. The distribution of signal strength vs. range was examined in an attempt to predict the maximum observable range. Fig. 6 shows the result. The actual quantity plotted along the x-axis is:

$$y = 10 \log_{10} \frac{1}{\rho_t^2 \rho_r^2}$$

where ρ_t is the range from the transmitter to the satellite
ρ_r is the range from the satellite to the receiving station.

This quantity represents the expected relative signal strengths from sources in the far field of both the transmitted and received beams. No clear trend is evident. There are several reasons for this. First, many satellites are in the near field of the Kickapoo transmitter, which extends to 7500 km. (The near field of our Maryland Point antenna extends only to 450 m. at this frequency.) Second, the variation in satellite cross-sections can cause a large scatter in this curve. Also, since this statistic was computed from the standard processing, the non-optimization can cause some satellite returns to appear weaker than they actually are. The principal determinant of the probability of detection was the azimuth of the satellite as viewed from the Maryland Point Observatory. Fig. 7 clearly shows the cutoff effect of the eastern end of the transmitter patterns.

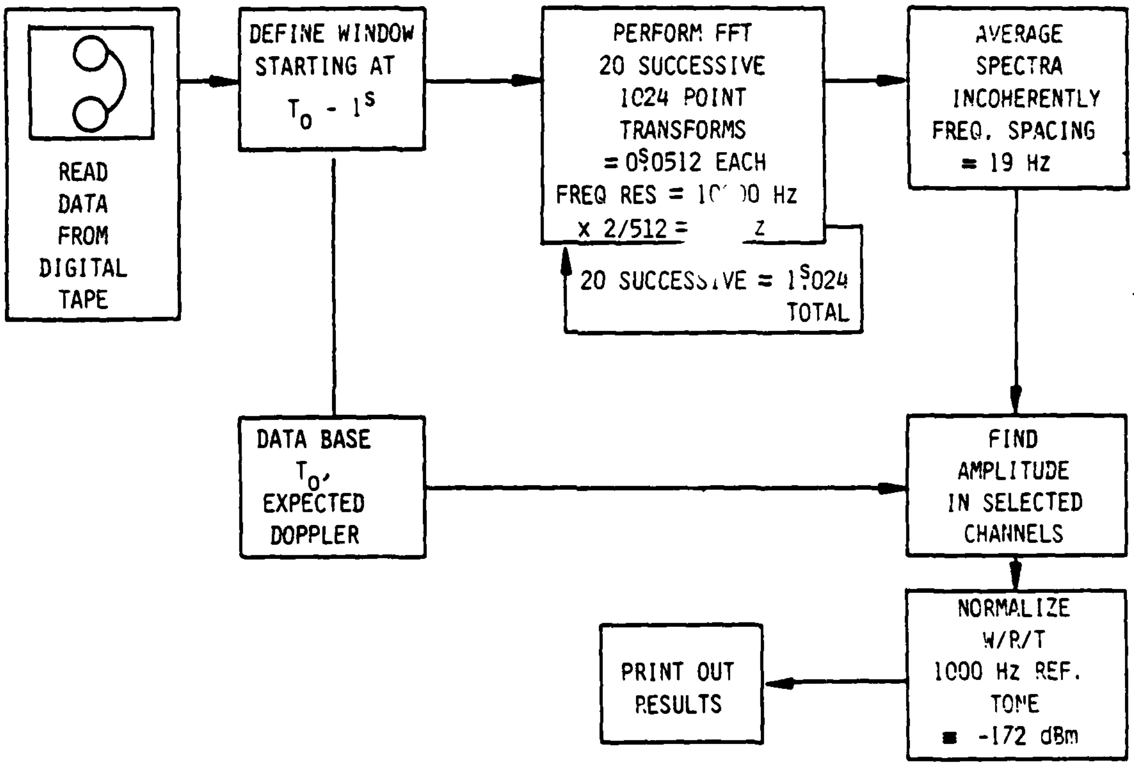

Fig. 3 — Flow diagram of standard processing

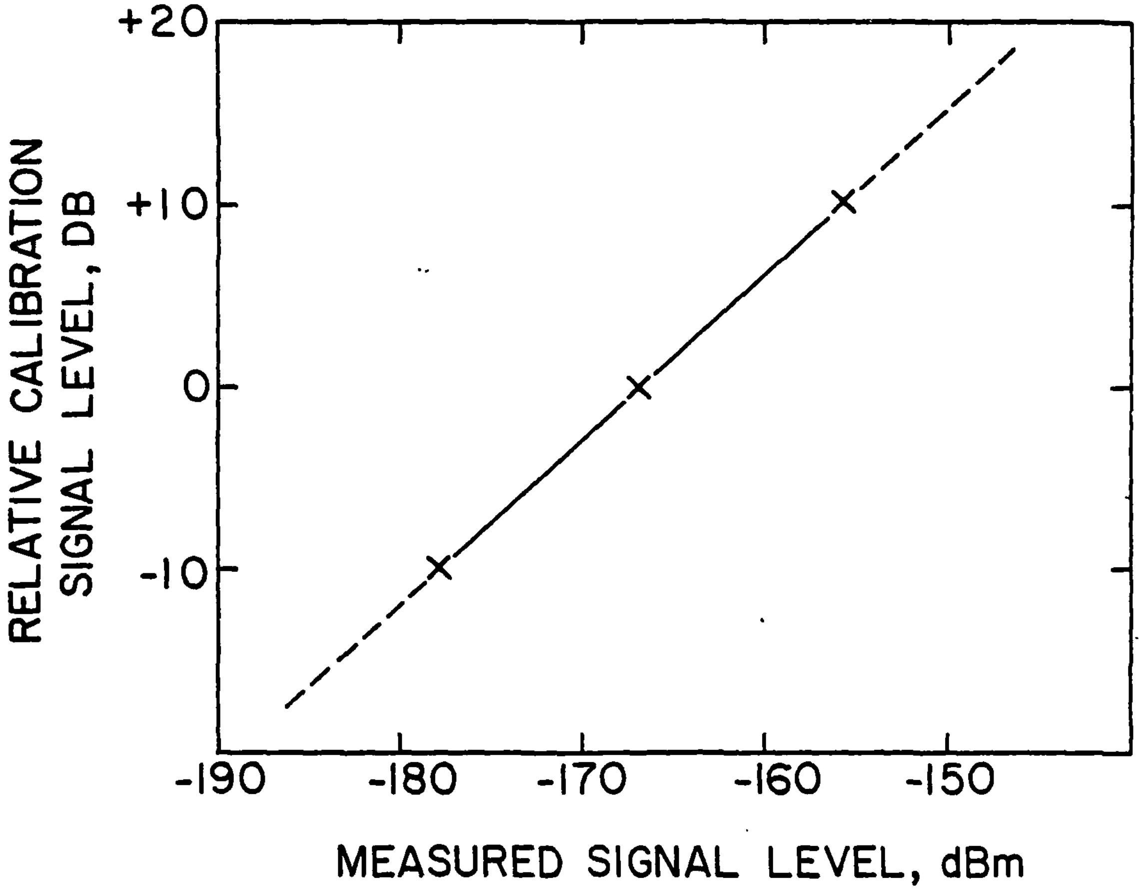

Fig. 4 — Measured linearity of signal strength determinations

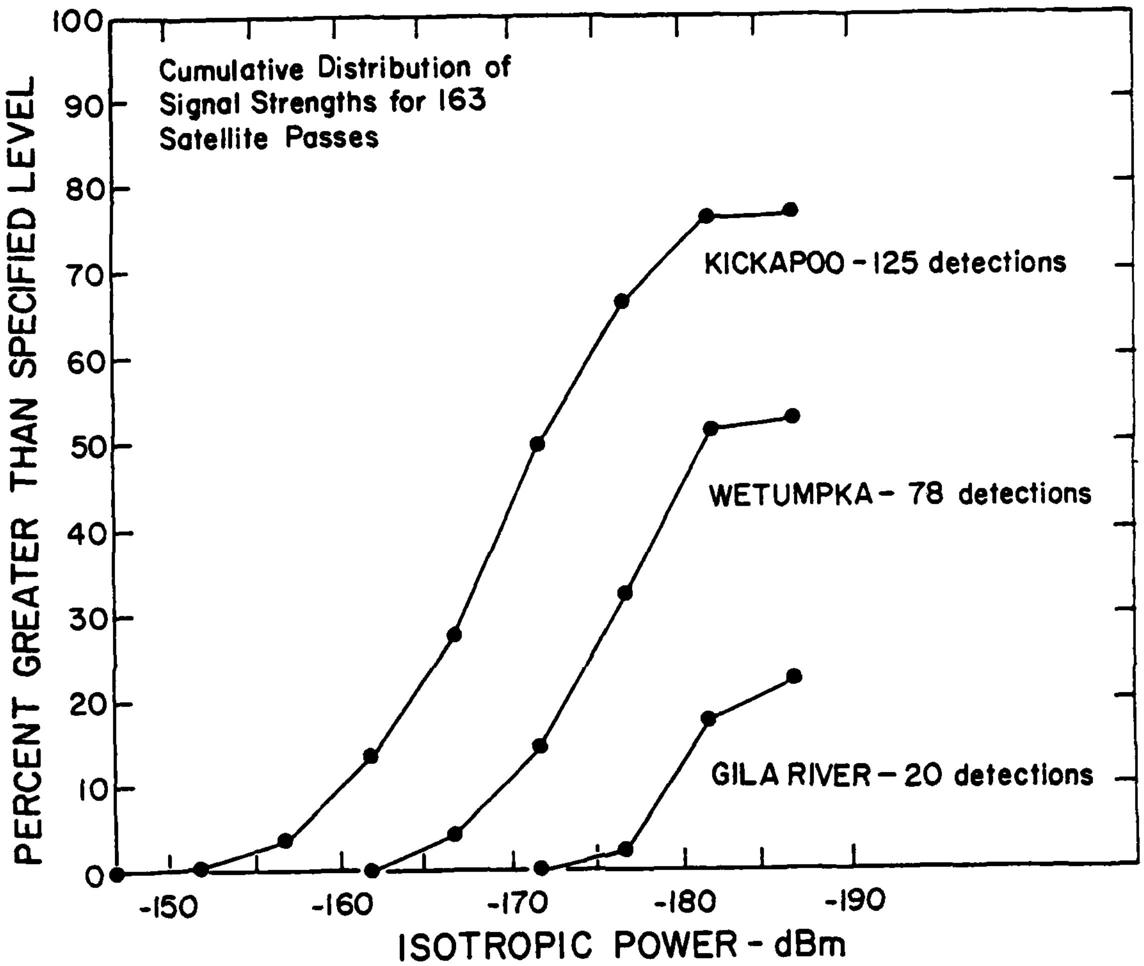

Fig. 5 — Cumulative distribution of signal strengths for the three NAVSPASUR transmitters

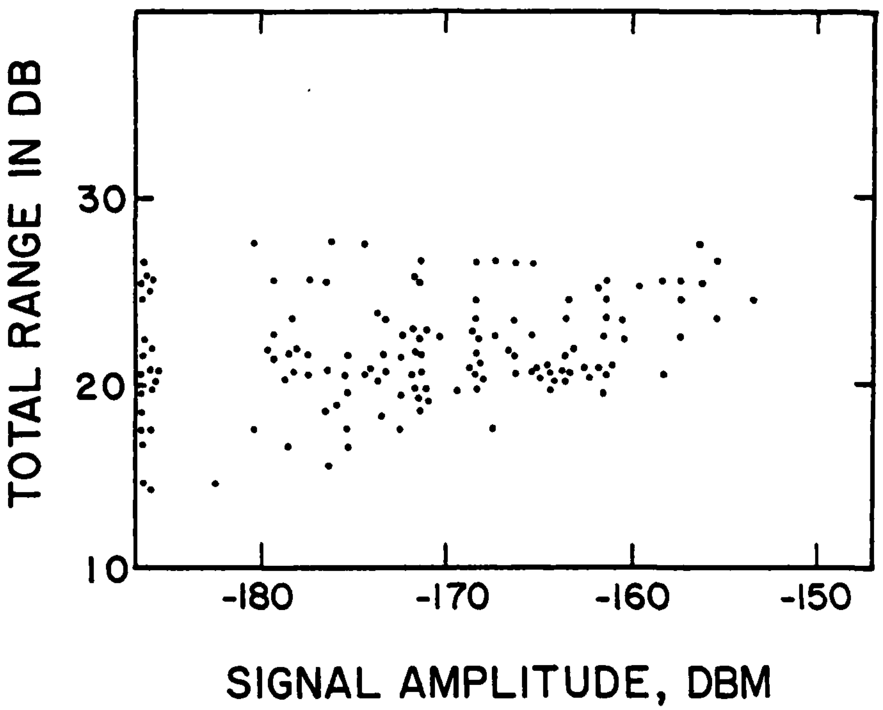

Fig. 6 — Measured signal strength as a function of range for Kickapoo signals. Non-detections are plotted along the left-hand edge of the plot.

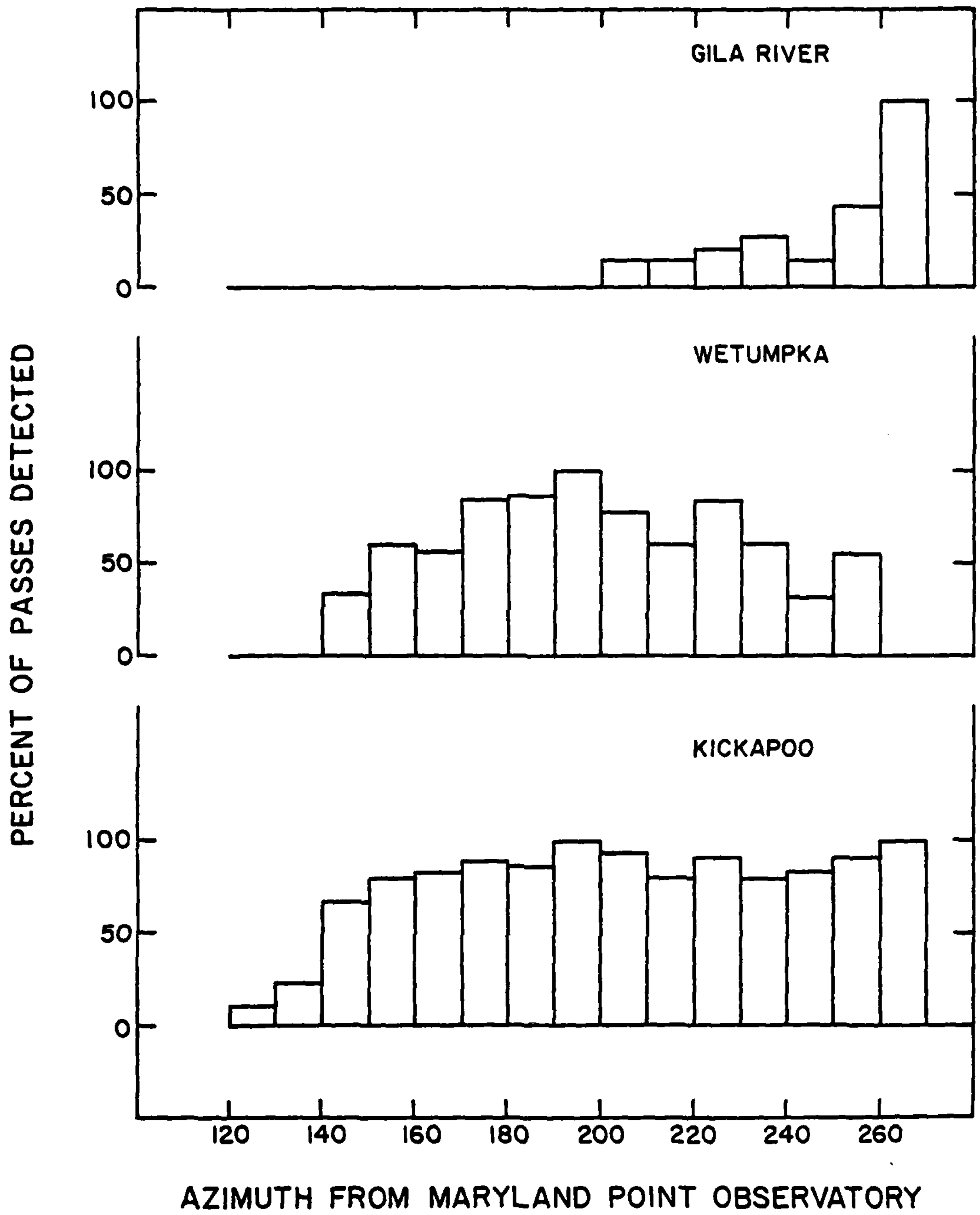

Fig. 7 — Detection percentage vs. azimuth

Fine Grain Analysis

A more thorough analysis was performed on a sample of 13 satellite returns; 12 of these were selected from a list supplied by the NAVSPASUR technical director and one was selected by S.K. because of its signal strength. In this analysis, we attempted to extract essentially all the information available concerning our sample satellite returns. This was easily possible because the data had been stored in digital form on magnetic tape, as described earlier. We had several specific objectives for this analysis. We wished to determine the maximum accuracy with which a doppler measurement could be made on a NAVSPASUR return using efficient signal processing. We then wished to apply these results to an orbital elements matrix to verify thes possiblity of determining all six elements of a satellite orbit accurately from one fence pass. In order to do this, "de-chirp" processing was developed, in which the linear rate of change of doppler shift of these selected satellite signals was removed. The chirp occurs while passing through the fence due to geometrical considerations. We also wished to examine the amplitude and frequency vs. time characteristics of several typical satellite passes to investigate reports of unusual characteristics in signal returns from the strong Kickapoo transmitter.

In order to do this, an interactive Fourier analysis package was developed to enable matching the signal processing parameters to the return being analysed. A flow diagram of the general signal analysis scheme is shown in Fig. 8. First, an intermediate data set was created by taking 256 successive 128-sample Fourier transforms and storing them on a disk. Since the one-bit method automatically normalizes the total power over the appropriate band, each intermediate spectrum was renormalized before storage by setting the mean of the frequency range 1200-2000 Hz, which should contain no signals, to a constant value. The total time window for this method was 1.6384 seconds; the starting time was adjustable, under operator control, within the T_0-4 seconds to T_0+2 seconds window recorded on the data tape. Each of the intermediate transforms spanned a time interval of 6.4 milliseconds, with a frequency resolution element of 156.25 Hz. (The numbers above are derived from the properties of Fourier transforms.) These intermediate transforms could then be operated upon to produce a series of spectrograms with any desired time resolution (1.384 seconds $> \tau >$ 0.0064 seconds) and frequency resolution (0.61 Hz $< \Delta f <$ 156.25 Hz) desired. This was done by performing a complex Fourier transform on the time series consisting of the complex amplitude belonging to a particular frequency channel or bucket. The resolution was normally chosen in binary fashion.

The normal analysis method was to first examine a series of 4 spectra each 0.4096 seconds long using a time window centered on the expected arrival time, and display these on an X-Y recorder (Fig. 9). The frequency bucket used corresponded to that in which the Kickapoo signal was expected (generally #13 or #14). If a signal was found, the actual arrival time was estimated, and the intermediate transforms were re-computed using this window center for further analysis. If no return was found, the rest of the tape window was searched to see if one could be located. When a signal was found, the 1000 Hz calibration signal was used to calibrate the amplitude scale. In addition, the apparent frequency of the calibrator was used as a scale factor to compensate for the ±1% speed fluctuations of the tape recorder. After calibration, de-chirp processing was performed upon the signal. The de-chirp processing amounted

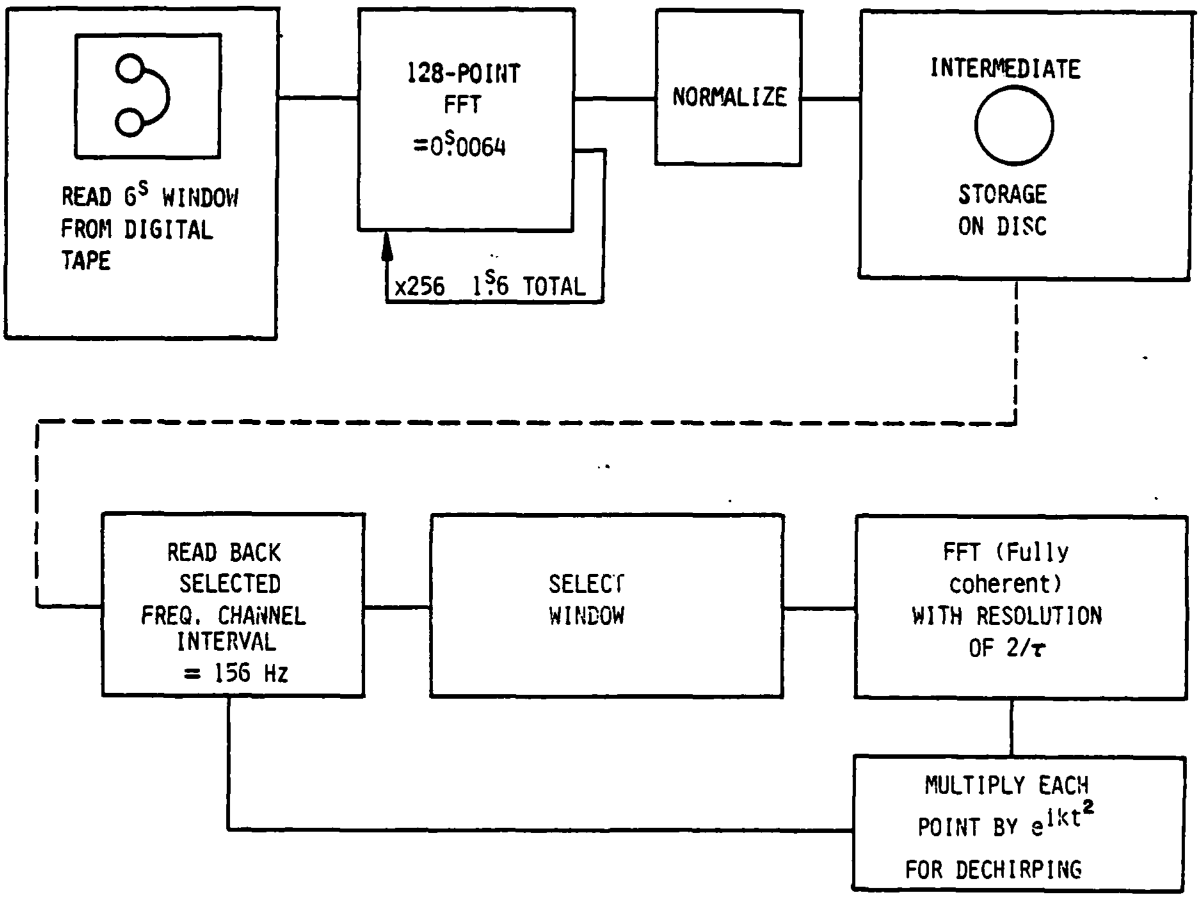

Fig. 8 — Flow diagram of high-resolution processing

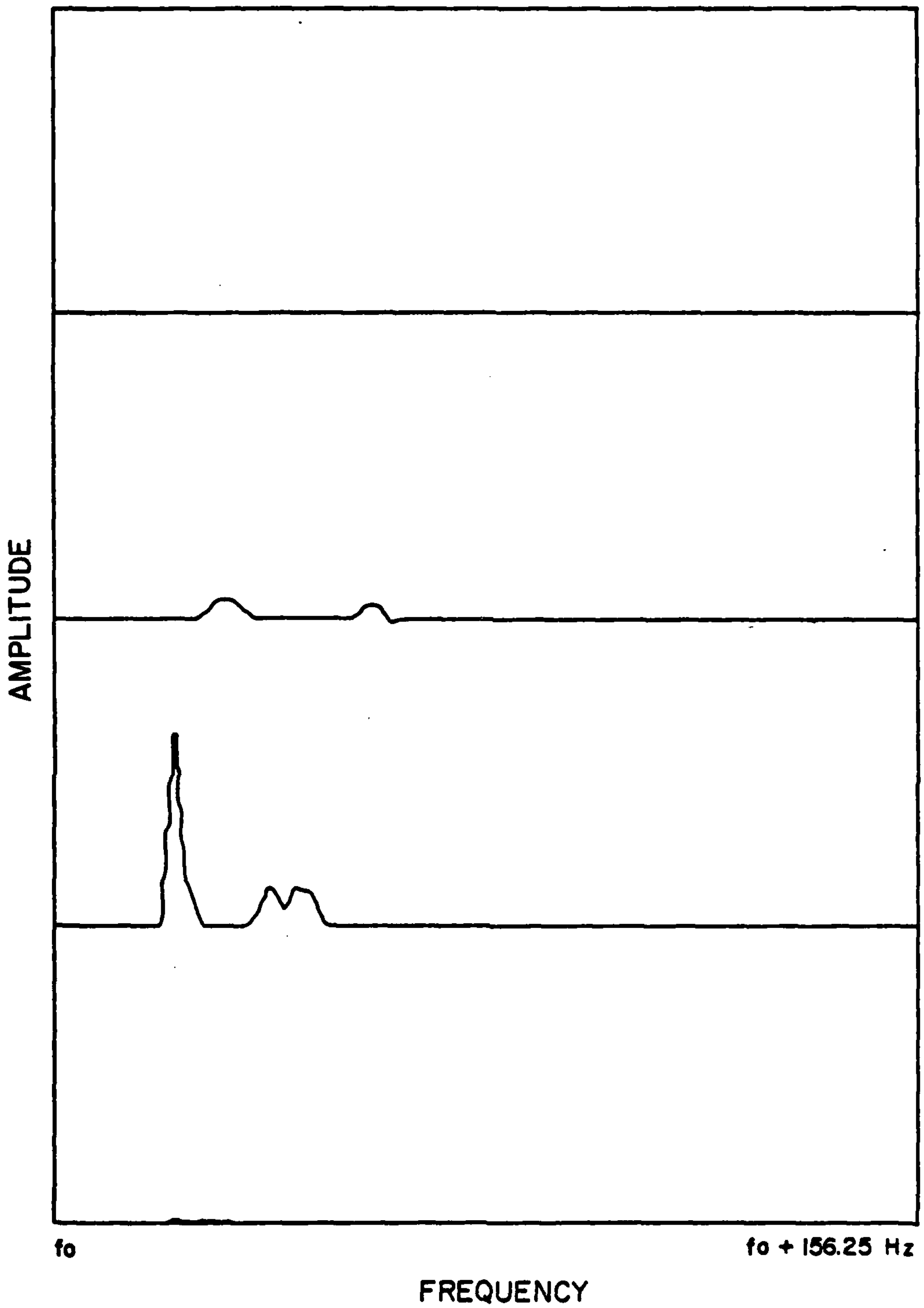

Fig. 9 — Determination of accurate arrival time from $0\overset{s}{.}4$ snapshots. Displacement of frequency axis between spectra #2 and #3 is due to chirp.

to mixing the signal with a chirped local oscillator; that is, one whose frequency varied at a linear rate. This rate was adjustable at will. This method was implemented in practice by making use of the relationship that for a constant rate-of-change in frequency

$$\frac{df}{dt} = K$$

the corresponding change in phase is

$$\Delta\Phi = \frac{K}{2} \cdot (t - t_0)^2$$

by integration. This change of phase was then applied to each of the (complex) intermediate power spectra before co-addition. This de-chirp processing, known to signal analysts as "chirp-z" processing, is an area of signal analysis in which the mathematical foundations are not well-understood. We assumed applicability. For all signals studied, the de-chirp processing proved to be a much improved way to extract information from the data. The de-chirp processing resulted in improved signal-to-noise ratio, greatly improved doppler shift accuracy, and an additional measurement element in the rate-of-change of doppler shift. Figure 10 illustrates a typical case of chirp processing for satellite #10561. As received, its chirp of approximately -20 Hz/sec spreads the received energy over a frequency range of about 7.5 Hz during the typical 0.5 second beam transit time. When the chirp is compensated for, the received power, which is an invariant, lines up within a frequency interval of 1.5 Hz, which is consistent with fully coherent addition for the signal transit time. In addition to a five-fold improvement in doppler shift accuracy, the signal amplitude, and thus signal-to-noise, is increased by a factor of 4. This result is typical of that realized on satellite returns by chirp matching.[§] Another interesting example of de-chirp processing is shown in Fig. 11. Here, we were able to clearly distinguish Kickapoo and Wetumpka signals separated by only 20 Hz because of their different chirp rates.

The results of our computation of doppler shift, chirp rate and amplitude are shown in Appendix C. In general, the results are consistent with the coarser standard analysis: #102 (rather strong) and #176 (quite weak) had been missed; conversely, #35 had produced a false detection, although at only -181 dBm level. We computed the doppler shift accuracy by the conservative method of determining the half-width of the signal return when de-chirped; as discussed below, much greater accuracy should be achievable for strong signals. In almost every case this was not more than the value predicted from Fourier theory for a coherent signal. The chirp rate accuracy was determined by a process of varying the chirp

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§ - The apparent displacement in doppler frequency that occurs as a function of chirp rate in this and all other figures in this report is an artifact due to the fact that our time origin was chosen at the beginning of the time window, 0.8 seconds before the signal return. Thus, the signal is displaced by an apparent frequency shift of 0.8 seconds times the chirp rate. This effect was compensated for in all doppler shift computations.

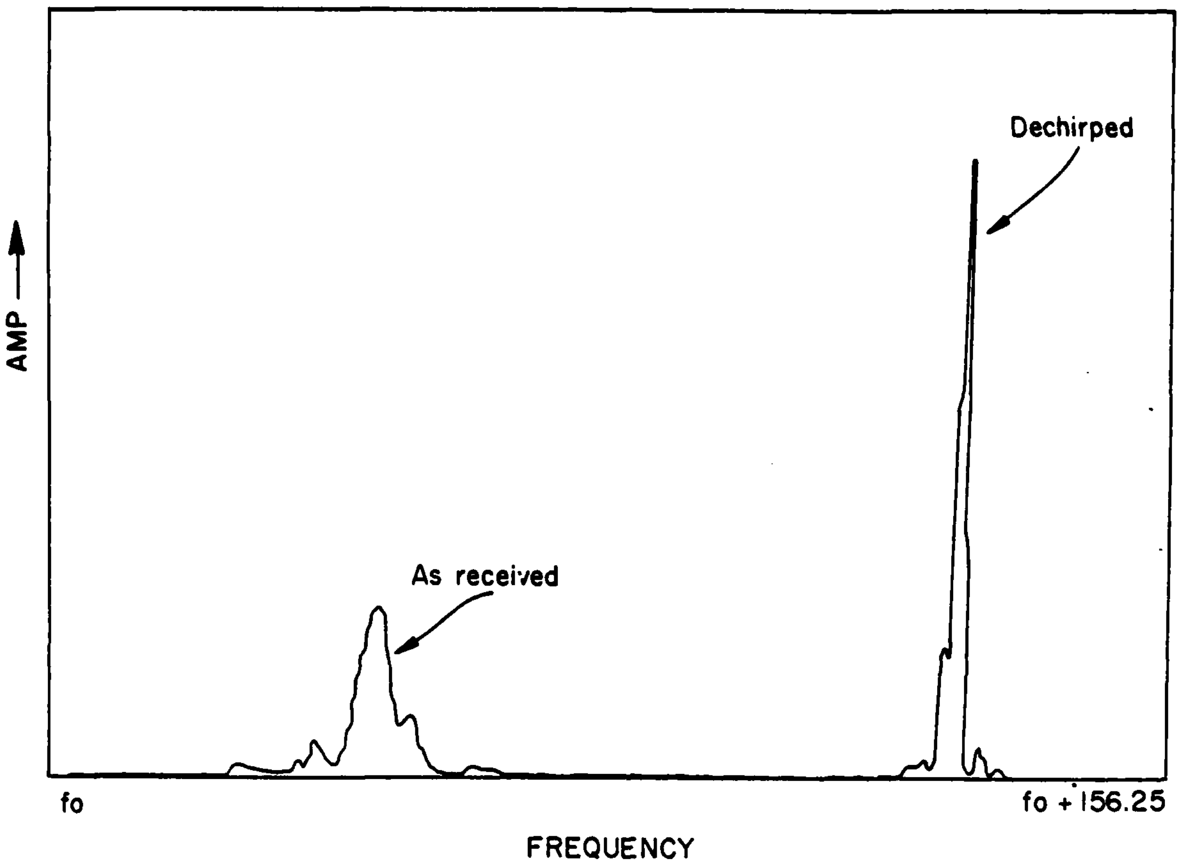

Fig. 10 — Illustration of de-chirp processing on satellite #10561

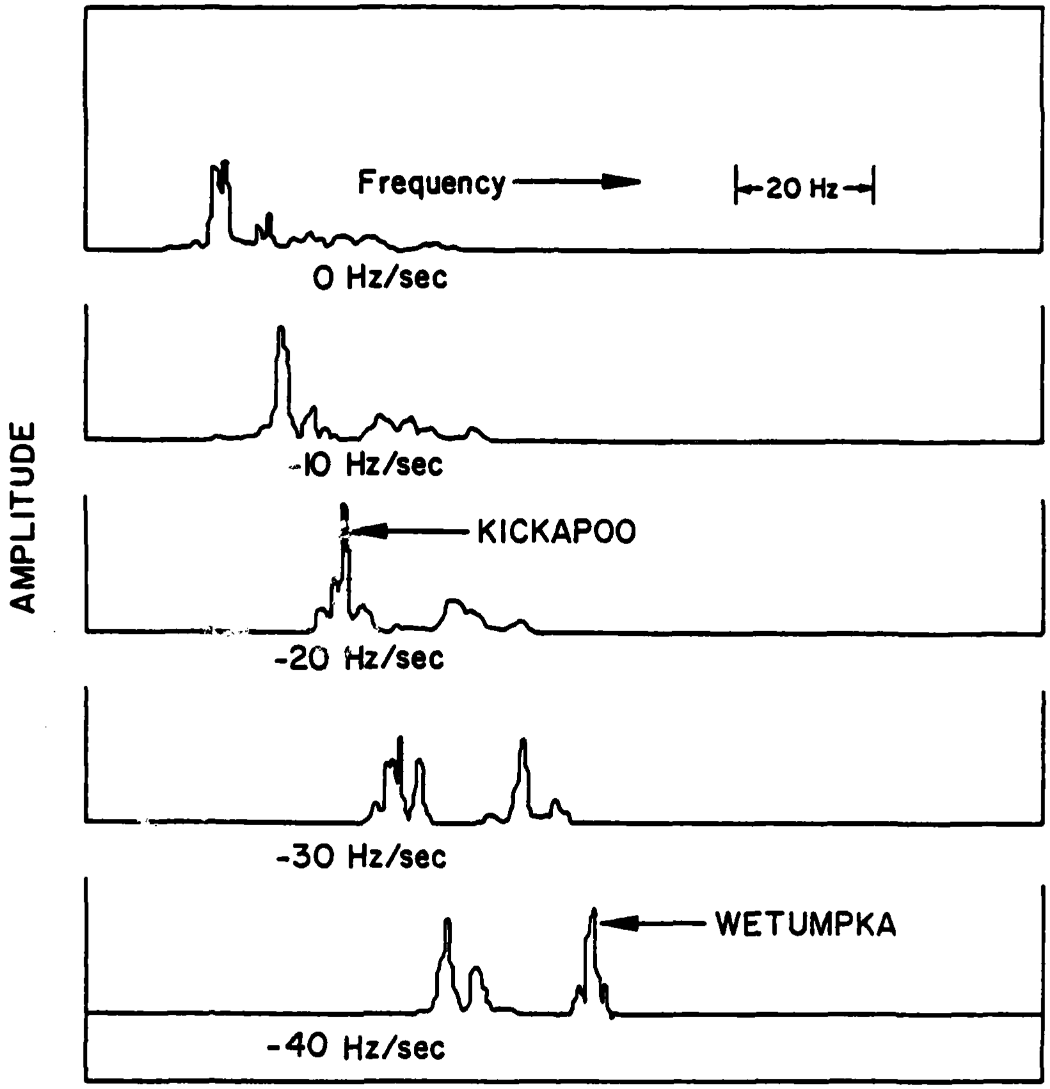

Fig. 11 — De-chirp processing applied to satellite #35, illustrating the ability to detect closely spaced Kickapoo and Wetumpka signals at different chirp rates

rate by ±1 Hz steps and determining when a clear difference in signal amplitude existed. The estimated accuracy of the chirp rate varied a great deal more than that of the doppler shift. This is expected, as the chirp rate determination is more affected by the details of the signal amplitude vs. time profile. The accuracy of chirp determination could also be greatly improved with a parametric statistic.

If a completely coherent signal (we define completely coherent as a single frequency sine wave) is measured for an interval τ, a Fourier transform of this signal has frequency buckets of width $1/\tau$, and a resolution of $1.2/\tau$ if uniform weighting is used. For a typical 0.5 second NAVSPASUR pass time, this amounts to a possible frequency measurement accuracy of 2 Hz. This is the "worst-case" measurement accuracy for a barely detectable signal (signal-to-noise ratio of 1:1) as long as it is fully coherent. For a strong signal there is the possibility of further improvement, as the accuracy of frequency measurement should be approximately inversely proportional to signal-to-noise ratio over some considerable range. For a S/N of 20 dB, which was typical of many of our observed satellites, this leads to a possible frequency measurement accuracy of 0.02 Hz. A typical NAVSPASUR satellite return had a chirp of -10 to -30 Hz/sec; this means that its doppler shift would spread out over a range of 5 to 15 Hertz and not allow this measurement accuracy. However, if its doppler shift is changing at a constant rate (or indeed any known $g(t)$), this can be compensated for as indicated above to enable full accuracy to be achieved. Chirp rate should also be measurable with a similar improvement proportional to the signal-to-noise ratio.

Our doppler shift measurements varied by up to ±20 Hz from the NAVSPASUR predictions. No systematic trend was evident. Chirp measurements for Kickapoo, however, were consistently about 10 Hz more positive than predictions, although Wetumpka chirp measurements agreed within ±2 Hz. The explanation lies presumably in a faulty geometry in the predictions. Usually close to 90% of the return energy could be de-chirped into the central return; for some satellites, as in the Kickapoo return in Fig. 11, appreciable sidebands were present. This phenomenon has not been investigated. Returns as the satellite transits an antenna sidelobe should, in general, dechirp in the same manner as the main lobe return. However, further study of the expected chirp pattern is indicated because phase shifts are known to take place between main and side lobes, and also if the target is in the near field of the antenna, as is often the case for the Kickapoo array.

A limited investigation was undertaken of the amplitude characteristics of satellite returns. Figure 12 shows a typical amplitude vs. time plot. The pass duration, about 0.5 seconds, was similar for all satellites. Many showed a surprising deep fading with an unexpectedly high fading frequency in the 10 Hz range. This would require a satellite rotation rate higher than seems physically plausible. No alternative explanation can be suggested at this time.

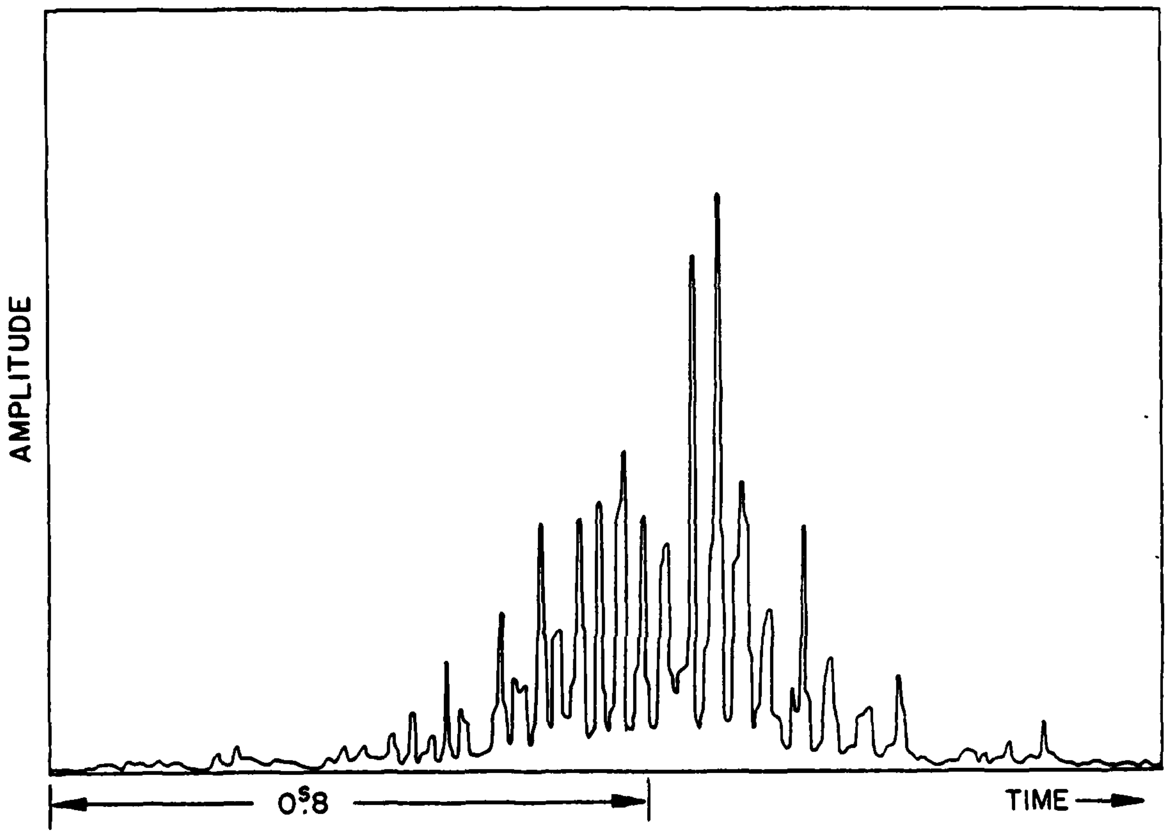

Fig. 12 – Amplitude vs. time plot of typical NAVSPASUR satellite pass

Applications to Orbital Determinations

This preliminary investigation has clearly demonstrated that it is possible to receive many satellite returns with adequate signal strength from an out-of-plane NAVSPASUR station located in the vicinity of Dahlgren, Virginia. We have also demonstrated that it is possible to determine, for a typical signal, both doppler shift and chirp to a much higher precision than is customarily done in the NAVSPASUR system. Unfortunately, it was not possible with our present data to take the further step of actually determining a one-pass orbit from our out-of-plane data together with the standard observables from the fence. This was because the raw data for our observing dates were not saved at NAVSPASUR headquarters when the standard daily data compression was done. To do this realistic simulation is a first priority for future work.

Although a direct determination of a one-pass orbit using our data was not possible, our improved signal strengths and doppler shift and chirp error bounds provide important support to the hypothesis that an out-of-plane station and/or improved observation modes can greatly improve the determination of off-plane doppler shift. Calculations to illustrate this are given in tables II and III. These results are numerical results computed by R.S. using the known computable error covariance matrix for the appropriate geometry, together with error estimates for the quantities in question. They thus represent realistic simulations of the accuracies to be expected. Table II illustrates, for a typical satellite geometry, the accuracies achievable in measurement of the plane-normal velocity† for the existing system and for various enhancements. The existing, or baseline system, has a measurement accuracy of ±20 Hz in doppler shift and ±0.0015/sec in the rate of change of the direction cosines. This gives for a sample satellite an off-plane velocity accuracy σ_V of ±95 km/min. If the doppler measurement accuracy is improved to ±1 Hz, σ_V improves only slightly, to ±79 km/min, indicating that this improvement is clearly not worth implementing for this purpose. An improvement in measuring the direction cosine rate m' to 0.00015/sec is effective in improving σ_V to 9.6 km/min. The most dramatic improvement in σ_V measurement would come by implementing chirp processing. For a test case with only chirp processing added, the σ_V measurement accuracy is improved by 25X, to 3.8 km/min. As mentioned above, we have shown that chirp processing is clearly feasible, with measured accuracies between 1 and 5 Hz/sec. This results in a σ_V measurement accuracy of between 3 and 20 km/min. Improving doppler shift and direction cosine rate accuracy adds very little if chirp processing is already implemented, as shown in the first "maximal accuracy" case. In any event ±1 Hz doppler processing is a necessary by-product of chirp processing.

For an out-of-plane station, similar improvements can be obtained without chirp processing. A station at Dahlgren, with standard processing, gives an improvement in σ_V to 8.2 km/min, while one at latitude +45°, with better geometry, causes even better results, with σ_V = 4.2 km/min. Expected signal strengths should be less for the northern station, however. With the use of chirp processing at the main station combined with doppler measurement at the off-plane station, even better accuracies can be obtained; 0.3 km/min for a Dahlgren station and 0.2 km/min for a +45° station.

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† The phrase 'plane-normal velocity' refers to the component of the satellite velocity normal to the NAVSPASUR fence.

Table II

Selected Computations Illustrating Improvement in Off-Plane Doppler Shift Determination Resulting from Utilization of Various Proposed Improvements in NAVSPASUR System, Including

A - Maximum Accuracy Doppler Shift Determination
B - Use of Chirp Information
C - Use of Out-of-Plane Station at (a) 45° latitude, or (b) approximate Dahlgren, Va. co-ordinates
D - Flutter of the NAVSPASUR fence by 1°.

Results are for a typical satellite geometry with altitude = 1200 n.m., inclination = 65°, and pass longitude = 99°W.

Case	σ_f Hz.	$\sigma_{m'}$ 1/sec	$\sigma_{f'}$ Hz/sec	f_{Dahl}	$f_{45°}$	flutter	σ_v km/min
Baseline	20	0.0015	-	-	-	-	94.94
Improved Observation Modes:							
f	1	0.0015	-	-	-	-	79.17
m'	20	0.0007	-	-	-	-	44.34
m'	20	0.00015	-	-	-	-	9.50
f'	20	0.0015	20	-	-	-	55.34
f'	20	0.0015	1	-	-	-	3.47
Out-of-Plane Station:							
f_{Dahl}	20	0.0015	-	✓	-	-	8.06
f_{Dahl}+flutter	20	0.0015	-	✓	-	✓	2.32
$f_{45°}$	20	0.0015	-	-	✓	-	3.85
$f_{45°}$+ flutter	20	0.0015	-	-	✓	✓	2.16
flutter	20	0.0015	-	-	-	✓	2.79
Maximal Accuracy:							
f,m',f'	1	0.00015	1	-	-	-	3.21
f_{Dahl}	1	0.00015	1	✓	-	-	0.42
f_{Dahl}+flutter	1	0.00015	1	✓	-	✓	0.27
$f_{45°}$	1	0.00015	1	-	✓	-	0.23
$f_{45°}$ + flutter	1	0.00015	1	-	✓	✓	0.14
flutter	1	0.00015	1	-	-	✓	0.65

Symbols: f = doppler shift
m' = rate of change of direction cosines
f' = rate of change of doppler shift = chirp
Dahl refers to a station at the approximate location of Dahlgren, Va.
45° refers to a station at 45° north latitude

Table III — A comparison of improvement in NAVSPASUR plane-normal doppler shift determination from out-of-plane stations for satellites at various altitudes

Altitude n.m.	Current Off-Plane Velocity Accuracy km/min	Improved Velocity Accuracy +45°	Dahlgren
19200	1311	51	93
14700	1005	39	71
10800	741	29	53
7500	517	22	37
4800	334	14	25
2700	193	8.2	15
1200	95	4.2	8.1

An alternate system improvement is to flutter the transmitted beam by about 1° in a north-south direction to enable two sequential detections of a satellite on each pass. While implementation problems are associated with this, it could produce σ_v accuracies comparable to an out-of-plane station. The highest accuracy case, with a σ_v error of ±0.16 km/min, is obtained by using an out-of-plane station together with chirp processing and beam flutter; however, it is unrealistic to expect implementation of all three of these improved operating modes.

Table III illustrates the accuracy in off-plane velocity as a function of satellite altitude. As expected, σ_v accuracy becomes worse as the satellite altitude increases, because of the poorer geometry; the ratios between current accuracy, accuracy at a Dahlgren site and accuracy at a +45° site remain almost constant.

Further investigations are indicated to obtain full experimental confirmation of our predicted orbital accuracy improvements, apply our improved measurement methods to the NAVSPASUR system, and to investigate further some still-unexplained characteristics of the NAVSPASUR signals such as the observed rapid fading.

Acknowledgments

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3 - J. M. Moran, pp. 182-183 of "Methods of Experimental Physics, Vol. 12, Part C, - Astrophysics - Radio Observations", M. L. Meeks, ed., Academic Press, New York, 1976

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5 - "Handbook for NAVSPASUR System Orientation, Volume I", Naval Space Surveillance System, Dahlgren, Va., 1 July 1976

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APPENDIX A

NAVSPASUR SATELLITES OBSERVED AT MARYLAND POINT 5/7-8/81

1571	1586	1586	2801	3158	3229	3576	3818
4254	4254	4386	4387	4388	4388	4564	4578
4588	4813	5180	5211	5213	5214	5549	5550
5551	5552	5554	5614	5683	5731	6079	6118
6120	6121	6122	6262	6265	6266	6270	6392
6678	6682	6851	6852	6907	6986	6989	6990
6991	7005	7209	7272	7274	7291	7424	7424
7435	7440	7490	7490	7663	7678	7684	7714
7768	7823	7824	7825	7827	7827	8072	8287
8291	8419	8799	8873	8889	8892	9011	9011
9025	9481	9509	9588	9591	9593	9594	9610
9737	9846	9853	9903	10019	10141	10282	10288
10289	10290	10292	10362	10491	10514	10520	10561
10589	10589	10590	10676	10744	10776	10930	10935
10961	11042	11044	11045	11049	11084	11086	11111
11129	11130	11130	11130	11133	11134	11135	11165
11168	11251	11297	11302	11303	11303	11320	11326
11331	11425	11510	11540	11542	11543	11544	11573
11600	11680	11680	11695	11697	11750	11875	11876
11879	12054	12071	12107	12109	12114	12149	12320
12325	12327						

APPENDIX B

NAVSPASUR SATELLITE DETECTIONS

NRL NO.	DATE	TIME	SAT NO.	KICKAPOO AMP.	KICKAPOO FREQ.	WETUMPKA AMP.	WETUMPKA FREQ.	GILA RIVER AMP.	GILA RIVER FREQ.
4	81 5 7	16 45 15	10	-156	2204.3	UNABLE			
5	81 5 7	16 46 15	0	-167	2204.7	UNABLE			
6	81 5 7	17 47 15	-10	-178	2197.6	UNABLE		TEST	
7	81 5 7	16 48 15	-20	NO DETECTION		NO DETECTION		SIGNALS	
8	81 5 7	16 49 15	-30	NO DETECTION		NO DETECTION			
9	81 5 7	16 50 15	-40	NO DETECTION		NO DETECTION			
10	81 5 7	16 59 31	6266	-176	-4447.7	-177	-3981.7	NO DETECTION	
11	81 5 7	17 8 40	10362	-181	3264.8	-181	3142.3	UNABLE	
12	81 5 7	17 15 39	7490	-176	4007.6	UNABLE			
13	81 5 7	17 23 16	5549	-163	-3222.1	-177	-2304.1	NO DETECTION	
14	81 5 7	17 28 28	7440	NO DETECTION		NO DETECTION			
15	81 5 7	17 33 20	9481	-156	-3093.0	-174	-1988.3	-179	-3238.4
16	81 5 7	17 39 54	5731	-164	-5060.3	-163	-4807.1		
17	81 5 7	17 44 13	7824	NO DETECTION		NO DETECTION			
18	81 5 7	17 51 3	8889	-168	-742.6	-178	369.2	-178	-1522.8
19	81 5 7	17 58 39	3818	-173	-2313.9	NO DETECTION		NO DETECTION	
20	81 5 7	18 5 13	6678	-179	-851.9	NO DETECTION		NO DETECTION	
21	81 5 7	18 10 24	1586	-173	439.4	-181	1105.9	NO DETECTION	
22	81 5 7	18 15 29	7823	-173	-2317.6	-180	-1067.6	-182	-2684.4
23	81 5 7	18 22 26	5554	-173	1936.9	-176	2126.9	UNABLE	
24	81 5 7	18 27 58	10282	-166	-2156.1	-176	-872.1	NO DETECTION	
25	81 5 7	18 33 26	9594	-171	-3492.4	-178	-2690.0	NO DETECTION	
26	81 5 7	18 37 25	12325	-179	-4716.4	NO DETECTION		NO DETECTION	
27	81 5 7	18 41 18	11876	NO DETECTION		-182	-3675.4	NO DETECTION	
28	81 5 7	18 46 17	11130	-172	-3493.9	NO DETECTION		NO DETECTION	
29	81 5 7	18 51 43	6120	-179	-4868.5	NO DETECTION		NO DETECTION	
30	81 5 7	18 59 21	7490	-163	2350.1	-171	2719.2	UNABLE	
31	81 5 7	19 3 10	11875	-169	-2853.3	-181	-1806.3	NO DETECTION	
32	81 5 7	19 5 10	8892	NO DETECTION		NO DETECTION		-179	-1814.1
33	81 5 7	19 9 45	4254	-165	3710.7	-167	2686.6	NO DETECTION	
34	81 5 7	19 14 5	10676	-172	3247.9	UNABLE			
35	81 5 7	19 17 35	10520	-161	3284.7	UNABLE			
36	81 5 7	19 22 37	11695	-167	-3403.4	-178	-2571.2	-182	-3562.4
37	81 5 7	19 27 7	12114	-174	-2288.1	-175	-1036.7	NO DETECTION	
38	81 5 7	19 32 39	10141	-172	4106.5	NO DETECTION			
39	81 5 7	19 36 54	11303	NO DETECTION		NO DETECTION			
40	81 5 7	19 41 3	11425	-172	3242.0	UNABLE			
41	81 5 7	19 45 53	5213	-176	-1485.7	NO DETECTION		-182	-2055.8
42	81 5 7	19 50 7	7678	-178	-2093.1	NO DETECTION		NO DETECTION	
43	81 5 7	19 54 39	5550	-177	-2226.5	NO DETECTION		NO DETECTION	
44	81 5 7	20 0 53	8072	-160	3525.2	-164	3328.9	UNABLE	

NRL NO.	DATE	TIME	SAT NO.	KICKAPOO AMP.	KICKAPOO FREQ.	WETUMPKA AMP.	WETUMPKA FREQ.	GILA RIVER AMP.	GILA RIVER FREQ.
45	81 5 7	20 6 57	12320	-164	-606.2	-178	398.7	NO DETECTION	
46	81 5 7	20 11 36	10019	-163	3922.8	-171	3792.8		
47	81 5 7	20 16 47	11600	-166	4125.3	-167	3951.1		
48	81 5 7	20 22 42	10561	-154	4610.9	UNABLE			
49	81 5 7	20 28 25	12071	-157	3238.8	UNABLE		UNABLE	
50	81 5 7	20 32 41	11697	NO DETECTION		NO DETECTION		NO DETECTION	
52	81 5 7	20 43 17	10590	-172	-3182.6	-181	-2322.4	NO DETECTION	
53	81 5 7	20 49 25	10292	-180	-1386.2	NO DETECTION		NO DETECTION	
54	81 5 7	20 54 57	11049	-165	-2046.8	-179	-835.2	NO DETECTION	
55	81 5 7	21 0 19	10930	-169	-3624.7	-175	-2876.8	NO DETECTION	
56	81 5 7	21 8 3	11168	-177	3614.4	-181	3495.3		
57	81 5 7	21 13 3	10589	-162	-558.8	NO DETECTION		NO DETECTION	
58	81 5 7	21 28 24	7827	-174	-1260.1	-181	-14.9	NO DETECTION	
59	81 5 7	21 23 17	11680	-176	4117.6	UNABLE			
60	81 5 7	21 31 26	11303	-175	-502.3	NO DETECTION		-181	-1364.8
61	81 5 7	21 37 11	8287	-164	-808.4	-178	292.0	-179	-1583.1
62	81 5 7	21 41 12	9509	-170	4072.7	-175	3985.3		
63	81 5 7	21 46 34	5214	-166	-1983.3	NO DETECTION		NO DETECTION	
65	81 5 7	21 58 20	5551	-175	-2679.3	-278	-1730.6	NO DETECTION	
66	81 5 7	22 6 20	7684	-171	-3264.9	NO DETECTION		NO DETECTION	
67	81 5 7	22 14 21	6122	-164	-3812.5	-172	-3152.0	NO DETECTION	
68	81 5 7	22 26 43	11573	NO DETECTION		-173	-5070.7		
69	81 5 7	22 29 6	10961	-158	-4909.7	-169	-4189.9	UNABLE	
70	81 5 7	22 34 22	4588	-175	2412.2	-181	3527.0	NO DETECTION	
71	81 5 7	22 40 37	7424	-158	1948.7	NO DETECTION		NO DETECTION	
72	81 5 7	22 45 28	7663	-162	1729.4	-172	2000.6	UNABLE	
73	81 5 7	22 52 45	12149	-172	-5411.4	-174	-4739.8	NO DETECTION	
74	81 5 7	22 59 14	6907	-168	4629.8	UNABLE			
75	81 5 7	23 4 37	11510	-156	-3691.3	-176	-2232.4	-175	-3860.8
76	81 5 7	23 9 38	11680	-162	2172.9	UNABLE		UNABLE	
77	81 5 7	23 14 13	11165	-159	3105.3	-168	2975.4	UNABLE	
78	81 5 7	23 19 47	5180	-176	-5446.1	-177	-5181.7		
79	81 5 7	23 23 3	4386	NO DETECTION		NO DETECTION			
80	81 5 7	23 32 30	7209	-166	-5198.8	-174	-4933.9		
82	81 5 7	23 42 13	6265	NO DETECTION		NO DETECTION			
83	81 5 7	23 47 51	6682	-183	2206.5	UNABLE			
84	81 5 7	23 53 57	10514	-168	2303.5	-173	2522.8	UNABLE	
85	81 5 8	13 57 25	6118	-172	-4602.1	-179	-4178.2	UNABLE	
87	81 5 8	14 9 37	9011	NO DETECTION		NO DETECTION			
88	81 5 8	14 15 45	10491	-162	-3164.1	-173	-2518.1	NO DETECTION	
89	81 5 8	14 24 42	11086	NO DETECTION		NO DETECTION		NO DETECTION	

NRL NO.	DATE	TIME	SAT NO.	KICKAPOO AMP.	KICKAPOO FREQ.	WETUMPKA AMP.	WETUMPKA FREQ.	GILA RIVER AMP.	GILA RIVER FREQ.
90	81 5 8	14 30 1	6990	-175	-4231.3	NO DETECTION		NO DETECTION	
91	81 5 8	14 34 13	11084	-168	2558.0	-173	2359.4	UNABLE	
92	81 5 8	14 38 6	6270	-176	-4106.0	NO DETECTION		NO DETECTION	
93	81 5 8	14 44 44	6262	-164	-588.5	NO DETECTION		-181	-1453.2
94	81 5 8	14 50 32	11111	-172	-2730.4	-179	-670.8	NO DETECTION	
95	81 5 8	14 51 48	11326	-172	2518.0	-167	2339.9	NO DETECTION	
96	81 5 8	14 57 47	6079	-162	3768.8	-173	3636.7	UNABLE	
97	81 5 8	15 2 35	8873	NO DETECTION		-180	3896.7		
98	81 5 8	15 7 42	4388	NO DETECTION		NO DETECTION			
99	81 5 8	15 12 52	6851	-166	-2940.2	-174	-1890.1		
100	81 5 8	15 18 45	8419	-158	-1677.4	-174	-944.0	-181	-2040.6
101	81 5 8	15 24 49	7768	-171	3669.2	-165	3484.7	NO DETECTION	
102	81 5 8	15 29 43	11251	NO DETECTION		UNABLE			
103	81 5 8	15 32 43	11331	-176	-4169.5	-171	-3266.7	UNABLE	
104	81 5 8	15 38 20	5614	-174	-2346.8	NO DETECTION		NO DETECTION	
105	81 5 8	15 40 50	5211	-171	1804.4	NO DETECTION		NO DETECTION	
107	81 5 8	15 52 33	5552	-166	1948.9	-179	2239.7	NO DETECTION	
108	81 5 8	16 0 27	7435	-178	-1406.1	NO DETECTION		NO DETECTION	
109	81 5 8	16 5 43	4813	-151	-4641.0	-169	-4031.7		
110	81 5 8	16 7 40	9011	NO DETECTION		NO DETECTION		-182	1354.7
111	81 5 8	16 15 1	9610	-180	-4651.4	-168	-4368.7	UNABLE	
112	81 5 8	16 19 40	6991	NO DETECTION		NO DETECTION		NO DETECTION	
113	81 5 8	16 26 14	6852	-171	-2202.0	-176	-933.1	-182	-2578.4
114	81 5 8	16 30 22	9737	-162	2407.2	-183	2211.0	NO DETECTION	
116	81 5 8	16 42 30	6392	-164	3590.4	-179	3455.7	UNABLE	
117	81 5 8	16 49 43	11750	-167	2063.8	-174	2477.2	UNABLE	
118	81 5 8	16 52 0	6989	-179	-3212.8	NO DETECTION		-181	-3483.4
119	81 5 8	16 56 59	9846	-160	2433.9	-172	2282.1	UNABLE	
120	81 5 8	17 3 26	4388	-169	1944.5	NO DETECTION		NO DETECTION	
121	81 5 8	17 7 43	7005	-177	2279.5	-174	4157.1	NO DETECTION	
123	81 5 8	17 19 17	1586	-177	-162.7	NO DETECTION		UNABLE	
124	81 5 8	17 23 50	5683	-159	-5528.1	-171	-5206.8		
125	81 5 8	17 29 14	9903	NO DETECTION		NO DETECTION			
126	81 5 8	17 36 9	9594	NO DETECTION		NO DETECTION			
127	81 5 8	17 40 4	11042	NO DETECTION		NO DETECTION			
128	81 5 8	17 44 26	10935	NO DETECTION		NO DETECTION			
129	81 5 8	17 48 50	11130	NO DETECTION		NO DETECTION			
130	81 5 8	17 52 32	12109	NO DETECTION		NO DETECTION			

NRL NO.	DATE	TIME	SAT NO.	KICKAPOO		WETUMPKA		GILA RIVER	
				AMP.	FREQ.	AMP.	FREQ.	AMP.	FREQ.
131	81 5 8	17 55 57	12107	NO DETECTION		NO DETECTION			
132	81 5 8	18 0 6	11045	NO DETECTION		NO DETECTION			
133	81 5 8	18 3 33	8799	-169	4073.9	NO DETECTION			
134	81 5 8	18 9 31	9853	-168	-5489.6	-173	-5174.6		
135	81 5 8	18 13 12	7714	-167	2501.2	UNABLE		UNABLE	
136	81 5 8	18 18 30	11044	NO DETECTION		NO DETECTION		NO DETECTION	
137	81 5 8	18 24 2	11297	-172	-3466.0	-183	-2594.3	NO DETECTION	
138	81 5 8	18 28 18	11129	-174	-2972.8	-179	-1973.1	NO DETECTION	
139	81 5 8	18 29 38	7272	-169	-3130.9	-174	-2206.9	NO DETECTION	
140	81 5 8	18 36 16	10289	NO DETECTION		-178	-1649.9	NO DETECTION	
141	81 5 8	18 41 8	4254	-168	2488.0	-165	2618.1	UNABLE	
142	81 5 8	18 45 12	4578	-169	-6006.4	-171	-5679.4		
143	81 5 8	18 50 35	11133	NO DETECTION		NO DETECTION			
144	81 5 8	18 54 40	11543	-180	-4560.3	NO DETECTION		NO DETECTION	
145	81 5 8	19 1 13	10290	-176	-3073.6	NO DETECTION		NO DETECTION	
146	81 5 8	19 4 17	2801	-178	3376.1	NO DETECTION			
147	81 5 8	19 9 26	11879	-171	-3386.9	-177	-2559.3	NO DETECTION	
148	81 5 8	19 14 1	9591	NO DETECTION		NO DETECTION			
149	81 5 8	19 18 39	8291	-167	-2031.3	NO DETECTION		-183	-2464.7
150	81 5 8	19 22 55	11540	-172	-1741.5	NO DETECTION		NO DETECTION	
151	81 5 8	19 27 46	12054	-156	2226.7	NO DETECTION			
152	81 5 8	19 31 46	6986	-169	-1652.2	-183	-339.9	NO DETECTION	
153	81 5 8	19 35 47	11542	-168	-2123.5	NO DETECTION		NO DETECTION	
154	81 5 8	19 42 20	11130	-172	-537.7	-179	454.1	-177	-1402.0
155	81 5 8	19 47 20	6121	-176	-4391.9	-182	-3941.3	NO DETECTION	
156	81 5 8	19 51 33	10288	NO DETECTION		NO DETECTION			
157	81 5 8	19 56 5	11544	-164	-2208.0	NO DETECTION		NO DETECTION	
158	81 5 8	22 0 44	7825	-161	-1823.9	NO DETECTION		-181	-2250.3
159	81 5 8	20 6 4	12327	-164	-529.5	NO DETECTION		-180	-1392.1
160	81 5 8	20 10 32	11302	-165	-2720.8	NO DETECTION		NO DETECTION	
161	81 5 8	20 15 55	1571	-162	438.0	NO DETECTION		-183	-1121.3
162	81 5 8	20 23 00	10589	-165	-2251.4	-177	-1073.1	NO DETECTION	
163	81 5 8	20 28 22	7827	NO DETECTION		NO DETECTION		NO DETECTION	
165	81 5 8	20 39 20	4387	NO DETECTION		NO DETECTION			
166	81 5 8	20 45 31	11134	-178	-1252.3	-176	-21.1	NO DETECTION	
167	81 5 8	20 51 17	7274	-180	3210.4	NO DETECTION		UNABLE	
168	81 5 8	20 56 49	9025	NO DETECTION		NO DETECTION		NO DETECTION	
169	81 5 8	21 1 30	11135	NO DETECTION		NO DETECTION		NO DETECTION	
170	81 5 8	21 6 2	3158	NO DETECTION		-179	3325.6	NO DETECTION	
171	81 5 8	21 10 26	9593	NO DETECTION		NO DETECTION		NO DETECTION	
172	81 5 8	21 18 22	3229	-172	3430.7	UNABLE			
173	81 5 8	21 24 8	7424	-171	2251.4	UNABLE		UNABLE	
174	81 5 8	21 30 17	7291	NO DETECTION		NO DETECTION		NO DETECTION	
175	81 5 8	21 33 15	3576	-172	-3219.6	-169	-2082.5	-181	-3483.4
176	81 5 8	21 39 29	10776	NO DETECTION		NO DETECTION			
177	81 5 8	21 46 46	11320	-179	3888.0	-172	3749.6		
178	81 5 8	21 53 24	10744	-178	3648.7	-176	3477.5	UNABLE	
179	81 5 8	21 58 56	10961	NO DETECTION		NO DETECTION			

Appendix C

NAVSPASUR/NRL Satellite Report

Satellite No. 10362

Date and Time of Pass 81/05/07/17/08/40.4

NRL Control No. 11

Archive Data Available yes

Time of Arrival: Measured — Sigma Predicted +0.4

Kickapoo: not detected

Satellite No. 10520

Date and Time of Pass 81/05/07/19/17/34.6

NRL Control No. 35

Archive Data Available yes

Time of Arrival: Measured -0.44 Sigma 0.3 Predicted -0.4

Kickapoo:

Doppler	Measured	+3280.1	Sigma	1.	Predicted	3270.
Chirp	Measured	-20.	Sigma	5.	Predicted	-29.4
Amplitude	Measured	-160 dbm				

Wetumpka:

Doppler	Measured	+3301.4	Sigma	1.	Predicted	3286.
Chirp	Measured	-40.	Sigma	5.	Predicted	-42.3
Amplitude	Measured	-161 dbm				

Satellite No. 10141

Date and Time of Pass 81/05/07/19/32/39

NRL Control No. 38

Archive Data Available no

Time of Arrival: Measured +0.14 Sigma 0.3

Kickapoo:

Doppler Measured +4102.6 Sigma 1. Predicted 4090.

Chirp Measured -17. Sigma 10.

Amplitude Measured -173 dbm

Wetumpka: not detected

Satellite No. 10019

Date and Time of Pass 81/05/07/20/11/35.7

NRL Control No. 46

Archive Data Available yes

Time of Arrival: Measured -0.4 Sigma 0.3 Predicted -0.3

Kickapoo:

Doppler	Measured	+3919.8	Sigma	1.	Predicted	3906.
Chirp	Measured	-17.	Sigma	2.	Predicted	-25.3

Amplitude Measured -161 dbm

Wetumpka:

Doppler	Measured	+3798.2	Sigma	1.	Predicted	3781.
Chirp	Measured	-34.	Sigma	2.	Predicted	-34.2

Amplitude Measured -167 dbm

Satellite No. 10561

Date and Time of Pass 81/05/07/20/22/41.8

NRL Control No. 48

Archive Data Available yes

Time of Arrival: Measured -0.36 Sigma 0.3 Predicted -0.2

Kickapoo:

Doppler	Measured	+4594.	Sigma	1.	Predicted	4592.
Chirp	Measured	-18.	Sigma	1.	Predicted	-27.7
Amplitude	Measured	-149 dbm				

Wetumpka:

Doppler	Measured	+4552.	Sigma	1.	Predicted	4529.
Chirp	Measured	-42.	Sigma	1.	Predicted	-42.2
Amplitude	Measured	-159 dbm				

Satellite No. 11165

Date and Time of Pass 81/05/07/23/14/13.0

NRL Control No. 77

Archive Data Available yes

Time of Arrival: Measured +0.3 Sigma .3 Predicted 0.0

Kickapoo:

Doppler	Measured	+3108.1	Sigma	1.	Predicted	3093.
Chirp	Measured	-17.4	Sigma	1.	Predicted	-38.1
Amplitude	Measured	-153 dbm				

Wetumpka:

Doppler	Measured	+2985.9	Sigma	1.	Predicted	2962.
Chirp	Measured	-57	Sigma	1.	Predicted	-57.4
Amplitude	Measured	-160 dbm				

Gila River: not detected

Satellite No. 10514

Date and Time of Pass 81/05/07/23/53/56.6

NRL Control No. 84

Archive Data Available yes

Time of Arrival: Measured -0.06 Sigma 0.3 Predicted -0.4

Kickapoo:

Doppler	Measured	+2312.0	Sigma	1.	Predicted	2296.
Chirp	Measured	-17.	Sigma	10.	Predicted	-46.6
Amplitude	Measured	-159 dbm				

Wetumpka:

Doppler	Measured	+2542.0	Sigma	1.	Predicted	2522.
Chirp	Measured	-47.5	Sigma	1.	Predicted	-46.2
Amplitude	Measured	-162 dbm				

Gila River:

Doppler	Measured	+2248.	Sigma	5.	Predicted	2242.
Chirp	Measured	-36.	Sigma	5.	Predicted	-29.9
Amplitude	Measured	-174 dbm				

Satellite No. 11084

Date and Time of Pass 81/05/08/14/34/13.0

NRL Control No. 91

Archive Data Available yes

Time of Arrival: Measured -0.38 Sigma 0.1 Predicted 0.0

Kickapoo:

Doppler	Measured	+2564.1	Sigma	1.	Predicted	2552.
Chirp	Measured	-12.	Sigma	1.	Predicted	-20.6

Amplitude Measured -165 dbm

Wetumpka:

Doppler	Measured	+2366.9	Sigma	1.	Predicted	2353.
Chirp	Measured	-25.	Sigma	1.	Predicted	-25.3

Amplitude Measured -165 dbm

Gila River: not detected

Satellite No. 11251

Date and Time of Pass 81/05/08/15/29/42.6

NRL Control No. 102

Archive Data Available yes

Time of Arrival: Measured -1.62 Sigma 0.1 Predicted -0.4

Kickapoo:

Doppler	Measured	-4037.7	Sigma	1.	Predicted	-4027.
Chirp	Measured	-4.9	Sigma	1.	Predicted	-33.7

Amplitude Measured -151 dbm

Wetumpka:

Doppler	Measured	-4076.8	Sigma	1.	Predicted	-4055.
Chirp	Measured	-60.	Sigma	2.	Predicted	-61.9

Amplitude Measured -156 dbm

Satellite No. 11750

Date and Time of Pass 81/05/08/16/49/43.1

NRL Control No. 117

Archive Data Available yes

Time of Arrival: Measured -0.14 Sigma .15 Predicted +0.1

Kickapoo:

Doppler	Measured	+2064.7	Sigma	1.	Predicted	2059.
Chirp	Measured	-15.8	Sigma	1.	Predicted	-28.3

Amplitude Measured -172 dbm

Wetumpka:

Doppler	Measured	+2409.0	Sigma	1.	Predicted	2470.
Chirp	Measured	-40.2	Sigma	1.	Predicted	-41.1

Amplitude Measured -169 dbm

Gila River: not detected

Satellite No. 10289

Date and Time of Pass 81/05/08/18/36/16.0

NRL Control No. 140

Archive Data Available yes

Time of Arrival: Measured -- Sigma Predicted +0.0

Kickapoo: not detected

Satellite No. 12054

Date and Time of Pass 81/05/08/19/27/46.0

NRL Control No. 151

Archive Data Available yes

Time of Arrival: Measured -0.25 Sigma 0.1 Predicted 0.0

Kickapoo:

Doppler	Measured	+2227.9	Sigma	1.	Predicted	2223.
Chirp	Measured	-18.	Sigma	1.	Predicted	-29.6
Amplitude	Measured	-148 dbm				

Wetumpka: not detected

Satellite No. 10776

Date and Time of Pass 81/05/08/21/39/29

NRL Control No. 176

Archive Data Available no

Time of Arrival: Measured -0.27 Sigma 0.1

Kickapoo:

Doppler	Measured	-5112.6	Sigma	2.	Predicted	-5095.
Chirp	Measured	12.	Sigma	5.		
Amplitude	Measured	-177 dbm				

Wetumpka: not detected